Arctic seismic acquisition and processing

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To meet the world's ever growing energy demand, the E&P industry is developing new technologies to find and drill for hydrocarbons in more challenging environments such as deep water or deep targets, and to enter areas of the world that had previously been closed to exploration activities, such as the Arctic. While the Arctic was looked at geologically several times in the last century, the technological challenges that it presents restricted activities to the periphery of this vast collection of basins. Despite the significant resource estimates shown in Figure 1, the extreme environmental conditions combined with the vast remoteness of this region have limited exploration and development efforts to date.

The most recent USGS estimates for yet to find (YTF) in the Arctic represent nearly 25% of the world's remaining undiscovered hydrocarbon resources. Of this potential, 84% is thought to exist in the offshore regions containing a P50 estimate of 90 BBO, 1667 TCF gas, and 44 BBO gas liquids (Bird et al., 2008). To date, 40 MBO and 1100 TCF have been discovered demonstrating an active petroleum system in the region. The vast majority of the region is estimated to have a field size distribution of 1–10 BBOE with the greatest current potential in the Alaskan and Russian Chukchi regions. These estimates vary significantly because of the paucity of geologic and geophysical data in the Arctic, but they consistently indicate large YTF resources. This article reviews some technologies developed to overcome barriers in the Arctic; the focus is exclusively offshore with marine towed-streamer seismic acquisition.

Barriers to the acquisition of marine seismic data in the Arctic essentially boil down to the extreme weather conditions and the extreme environmental sensitivity of these regions. Harsh operating conditions, including limited or no daylight, extreme cold temperatures, and unpredictable and varying ice concentrations and coverage, all shorten the time window for conventional seismic operations, pose extreme risks to in-water acquisition equipment, and introduce unwanted noise into the data. Furthermore, the remoteness of these areas introduces many health, safety, and environment (HSE) risks, and attendant logistical issues. Respect for the customs and livelihood of the indigenous population, including their dependence on marine wildlife, further limits seismic activities, both in terms of timing and the type of equipment used. These issues combined with the environmental, social, and political sensitivity toward this "last frontier" have restricted the quantity and quality of seismic data available in the Arctic.

ION Geophysical recognized the lack of modern marine seismic data in the Arctic several years ago and in 2006 began to acquire new long-offset 2D (9-km cable length, 18-s record) seismic data during open-water seasons utilizing traditional methods near the existing ice edge. Over the next three years, the company enhanced its capabilities by developing new technologies and techniques to gather seismic data under the ice.

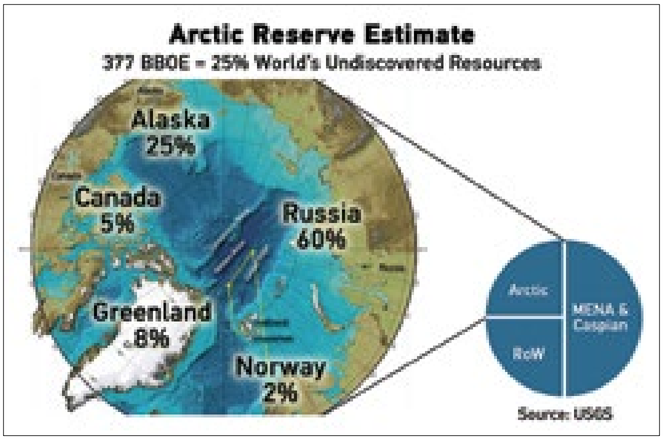

Figure 1. *Resource estimates and potential prize of the Arctic.*

Acquiring data in the Arctic has required the redefinition of many aspects of the seismic acquisition workflow, most notably moving traditional surface-referenced in-water marine acquisition equipment below the ice in the water column. A diverse team of marine seismic operations experts, geophysicists, vessel captains, ice pilots, and engineers experienced at operating vessels in ice was assembled to develop and operate specialized technologies and procedures to enable safe, efficient data acquisition. Mechanical, electrical, and systems engineers, navigation and positioning experts, project managers, and other specialists were added to the acquisition efforts to customize the technology and optimize all aspects of the workflow.

The equipment was carefully selected to overcome each barrier, including vessel type and class; in-water data acquisition equipment (considering durability, capability, and tolerances to temperature extremes); integrated navigation and positioning systems; and ice measurement, prediction and management tools. Additionally, methods were developed to deploy and maintain the in-water equipment to avoid loss and damage from the ice. From this experience, the project team identified a number of significant challenges that needed to be considered in the final workflow. Ultimately, a series of major challenges was investigated, and as a result, several integrated solutions were developed to acquire long-offset, high-quality seismic data in and under the Arctic ice. The remainder of this article will expand on some of these solutions.

Dual ice-class vessel operations

The first challenge required locating an ice-class seismic vessel. While this may seem obvious, the availability of seismic vessels that both have an ice rating sufficient to effectively operate safely in ice-covered conditions and simultaneously operate marine seismic acquisition equipment is limited.

To support the seismic vessel, an Arctic-class icebreaker would be required not only to create a track in the ice to ensure safe passage, but also to provide necessary support for operational safety. Using an icebreaker to escort a seismic vessel towing a long seismic streamer and source presents several new challenges. In traditional ice-escort missions, the icebreaker makes mission-critical decisions including steering a course to minimize ice breaking, determining the separation distance of vessels, as well as directing the escorted vessel to stop and wait while the icebreaker works its way through a difficult ridge or old ice.

Figure 2. *The challenges of the Arctic environment.*

Figure 3. *Dual vessel under-ice seismic operations.*

Figure 4. *Icebreaker* Oden *operating in close escort with seismic vessel during acquisition.*

Acquisition of seismic data in ice requires specialized operating procedures for vessel coordination and maneuvering. Unlike traditional ice-escort missions described above, the icebreaker must operate under the command of the escorted seismic vessel while simultaneously breaking a continuous track that has been predetermined by the seismic acquisition program. Additional complexities are introduced because the trailing seismic vessel is unable to stop while its equipment is deployed. This is a new and radically different operational scenario for the icebreaker and its crew. Like the ice-class seismic vessels, only a small fleet of icebreakers is available globally and securing access to the proper class of icebreaker for the anticipated ice regimes presents another significant challenge (Figure 2).

Experienced maritime professionals

Once the proper vessels have been identified, validated, and secured, ice-experienced maritime professionals are required to operate these vessels in ice-infested Arctic waters. The pool of individuals who meet these requirements is much like the pool of vessels that meet the requirements—limited. Understanding not only the vessel's ability to operate in ice (considering class and ice regime) but also having experience operating a vessel in ice is absolutely critical to the success of the operation. The maritime crew is truly challenged with a new paradigm of escorting a seismic vessel with deployed equipment.

Additionally, experienced ice pilots are needed to operate the integrated ice-management system. These individuals need to possess extensive senior maritime grade and experience operating vessels in ice as well as solid analytical abilities to develop trafficability studies in advance of the program and understand the real-time ice regimes and seismic requirements while on prospect. In addition, they must have good collaboration, team, and communication skills to work with the captain and bridge crew, as well as the other ice professionals on the project. Much like the vessels described above, these individuals are few and far between, and effort will need to be made to develop this skill set in the future.

Specialized procedures for ice operations

The challenge of operating in ice required the team to reassess the seismic workflow and develop a specialized ice-operations manual. Frigid air temperatures, combined with snow, ice, and low-light conditions challenged normal back-deck design and operations.

In particular, deployment and retrieval of the in-water equipment had to be thoroughly vetted, given the specialized equipment, to enable a completely subsurface acquisition capability for both source and streamer, as well as development of emergency retrieval procedures in the event of a sudden stoppage in the ice. Remote operations required revisiting emergency response plan (ERP) and medical evacuation considerations to ensure the operations could be conducted safely for all involved.

Integrated command and control system

Multivessel seismic operations require an integrated navigation system. While this is not necessarily unique to many other seismic operations, the challenges for this system include the ability to integrate a number of specific inputs including information from the ice-management system (radar and satellite images, tracking specific ice features, multiday forecasting, etc.) as well as seismic vessel track prediction. To improve real-time positioning for the start of line, the navigation system needs to take into account the set and drift of the ice and the relative position and speed of the icebreaker to the seismic vessel, and predict a course that enables the icebreaker to cut an offset track in the ice, allowing the seismic vessel and the towed streamer to be in position over the preplotted seismic line once they reach it. During open-water seismic acquisition programs, the seismic vessel can simply steer the preplotted line with slight adjustments for tide or current. For under-ice operations, the seismic vessel must follow the track provided by the icebreaker. Accordingly, the separation (distance and time) of the vessels and the set and drift of the ice require that the icebreaker cut a track in the ice in a prepredicted position (distance and time) such that the following seismic vessel can remain in the track and move along the originally preplotted seismic line position. This movement is evidenced in Figure 3.

Multivessel seismic operations are easily managed by today's modern navigation systems with one vessel, typically the master, and a second that is automatically steered to maintain a fixed relative position from the master. However, in ice operations, a third moving aspect must be accounted for—the presence and drift of ice around the seismic vessels and the in-water equipment.

Ice drifts in a direction that is usually different from the seismic vessel's movement, and opening a swath by an icebreaker in advance of the seismic vessel requires predicting where the icebreaker needs to be so that the open path falls over the desired line location when the seismic vessel reaches that point. In addition, an abeam movement of the ice field needs to be monitored until the towed streamer is clear of any deep keel ice obstructions (Figure 4).

Figure 5 depicts the dynamics associated with managing ice. If the ice conditions do not contain deep keel formations, this would not be a problem; however, in glacial and multiyear ice conditions, the keel depths can easily reach below a deep-tow cable configuration, requiring emergency dive procedures for steamer safety.

Orca command and control software is tightly integrated with ION's integrated ice-management system to make critical operational decisions quickly and intelligently.

Narwhal ice-management system

Understanding and managing the ice regime during under-ice seismic operations requires an integrated ice-management, navigation, positioning, and communication plan for the

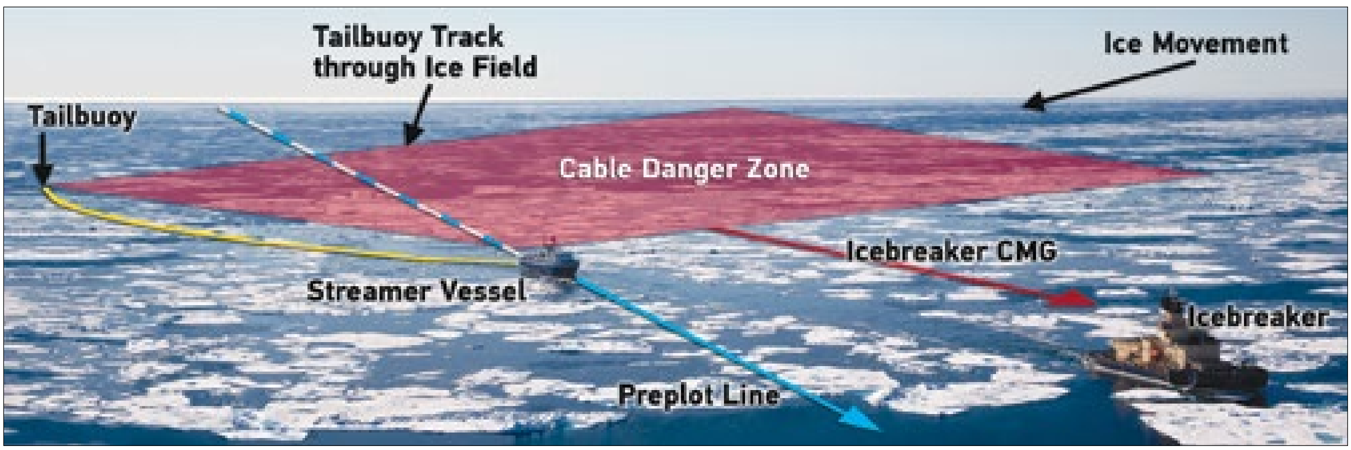

Figure 5. *Cartoon depicting the dynamics associated with managing ice.*

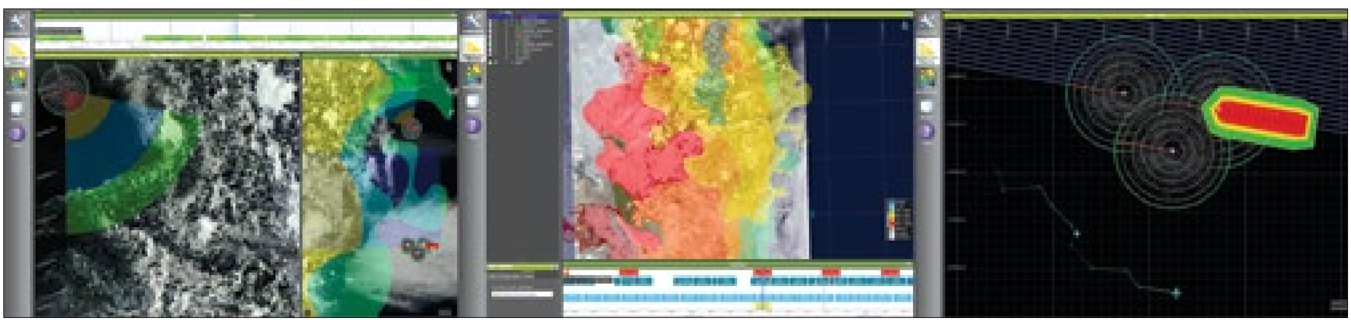

Figure 6. *Narwhal ice management system.*

vessels. Traditional ice-management systems, providing isolated insight and little-to-no integration, have remained largely unchanged for many years. Recognizing these limitations during its in-ice seismic operations, ION developed Narwhal, a proprietary integrated ice-management system to better inform and direct complex Arctic seismic operations. While this need originated from in-ice seismic operations, the system has application in commercial shipping and drilling operations.

Installed on all vessels in the operational network, this ice-management system is a distributed ice-management system designed for use by ice pilots, experts, and analysts. The system provides ice visualization, analysis, tracking, and risk mitigation tools for marine Arctic operations.

The integrated technology and communication protocol was established using existing ice-navigation, radar, and satellite imagery technology, combined with proprietary navigation and positioning software and a custom-built management plan for ice seismic operations. This protocol allows the vessels to share views and images from both bridges to manage vessel actions in real time and to plan future movements, based on ice scenarios, days and weeks in advance.

Utilizing ION Concept Systems' experience in multi-vessel command and control operations, this technology provides a powerful, flexible, and reliable communications layer, which maximizes the available bandwidth. The voice communications link between the icebreaker and the seismic vessel is critical. The ice pilots of both vessels need to remain in constant contact to discuss ice conditions and hazards immediately ahead of the fleet. For this, a link between vessels is dedicated strictly for the ice pilots.

Traditional ice management systems rely on marine ice hazard radar alone. Narwhal allows a greater number of inputs such as satellite imagery, ice charts and forecasts, metrological and sea conditions, air surveillance, and first-hand observations. The resultant integrated output provides operators with a more comprehensive understanding of the ice, which enables more informed decision-making (Figure 6).

Visualization and analysis tools are provided by integrated GIS multilayer display technology. Data layers include digitized ice hazard radar, satellite imagery, ice charts, forecasts, ice obstacles; tracking beacons and buoys, as well as standard GIS file formats. While the GIS display technology delivers the spatial picture, the Narwhal calendar adds the temporal aspect to bring the data to life. As users time-slide the calendar, the GIS displays updates, showing data relevant to the queried time. This spatial and temporal combination is a powerful tool, allowing the user to perform historical analysis.

Ice threats can be identified from manual observations, or imagery such as radar or satellite imagery. Threats are classified, logged to the central database, and tracked over time. The observed threat data are then used to build prediction models for each ice threat.

A variety of alarm zones can be defined and continually monitored for ice threat breaches. Predictions, time to impact, and time to react are factors in the alarm zone monitoring as the predicted scenario plays out. With an ice threat and alarm

Figure 7. *Specialized submersible floats.*

Figure 8. *The skeg for enabling subsea streamer deployment.*

level identified, analysts can plan a risk-mitigation strategy across the operational network and assign tasks to each icebreaker and support vessel.

With all data input time-stamped and logged to the central database, the system provides the comprehensive data management, reporting, and auditing facilities required in today's modern operations.

Specialized equipment

Given the extreme environment and potential for ice-related noise (vessels breaking ice, ice multiples, ice diffractions, etc.) to contaminate the seismic data, the choice of a seismic acquisition system required considerable investigation. A state-of-the-art seismic acquisition system was needed that not only would be robust and flexible enough to handle the cold air and water temperatures, but also rugged enough to withstand occasional but significant impact with ice, without failure. It needed to be able to record continuously to provide information for ice breaking by or ice collision with the lead icebreaker that would be initiated outside of the normal seismic record. The streamer also needs the ability to withstand significant depth exposure without component failure in the event that a sudden dive is required to avoid a deep ice keel, or a sudden stop during acquisition.

Under-ice deployment required moving all surface-referenced equipment deeper in the water column to avoid damage from the ice. Utilizing submerged floats developed by ION, seismic streamers and sources were towed at a specific depth under the ice. Specialized equipment built for under-ice seismic acquisition provides a huge advantage over standard practice configurations. The type of ice (thickness, concentration, and pressure), in combination with the seismic vessel's stern hull form, and its ability to leave an open tract can yield either a clear or a congested pathway behind the vessel, which can potentially damage any equipment at the surface (Figure 7).

Streamer and source positions are traditionally calculated in part by GPS measurements taken by floats and tailbuoys on the surface of the water. Any substantial ice concentration can easily destroy a float or tailbuoy device. Typically the tailbuoys are removed and the cable is positioned by compass units deployed along the cable. However, in light ice conditions, it is possible to devise an underwater tailbuoy capable of surfacing when able for a GPS fix, and providing a dead-reckoned or inertially aided position when GPS is lost under water. ION has fielded such a unit that can send raw positioning data from the tailbuoy GPS receiver to the vessel via FSK telemetry over spare wires in the DigiSTREAMER cable designed specifically for advanced positioning requirements. The GPS data can be differentially corrected onboard the vessel, eliminating the need for a radio connection to the tailbuoy as most dGPS or rGPS tailbuoys do.

When ice conditions are so severe that no tailbuoy could survive, magnetic-based compass headings must be relied upon for cable positioning. However, at high Arctic latitudes, the magnetic declination can change rapidly either spatially or temporally. Lines of only a few hundred kilometers can experience spatial declination changes of 10°, and isolated temporal changes can also be up to 10° over a small time period. Although an existing gridded declination solution could handle spatial variations, resolving both spatial and temporal variations required a second-order solution. ION developed a solution that includes a device (declinometer), which measures the magnetic declination as a function of time and position. The declinometer, now standard equipment on all ION Arctic surveys, measures the difference between a true (GPS) heading and a magnetometer measurement. This is no small feat as the declinometer must be calibrated to remove the hard and soft iron effects of a steel vessel that influences the magnetometer as well as compensating for the motion of that unit in three dimensions. The raw declination data interfaces with Orca for use in postprocessing the compasses and cable locations.

The air-gun source float is another towed device that is susceptible to ice damage. It is preferable to have a float that rides below the maximum keel depth of the ice. ION devised a system of source floats, both passive and active, to control the proper gun depth. Because vessels have widely varying source arrays, mounting configurations, and gun station weights, the system of passive floats needed to be custom-matched to each gun station. The solution was to build a passive float whereby multiple combinations of buoyant and flooded sections could be configured onboard to neutrally buoy each gun station. At the head of the subarray, an active gun float is used that has the ability to either raise or lower the float from the surface to the desired gun depth, as well as to actively trim the buoyancy in real time during acquisition. Similar to maintaining vehicle speeds, the active unit contains a microprocessor that internally controls the flow of air in and out of the float to maintain a set depth as commanded by the vessel software.

Another challenge was to develop a means to deploy and tow the streamer and source systems through the ice without damaging them. To address this challenge, an ice "skeg" was developed to provide a protective channel and submerged tow points for the streamer lead-in and source umbilicals. With this system, seismic equipment can be safely and efficiently towed through the broken ice column, with ice traveling around and under the vessel. Like many elements of this under-ice solution, subsequent developments resulted in skeg designs that are lighter and more efficient for vessel steering and seismic operations (Figure 8).

Processing Arctic marine seismic data

Operational challenges encountered during data acquisition are merely the first hurdles. Processing and imaging teams must also overcome unique challenges posed by the acquired data. The tough operational environment often leads to uncommon modes of noise being generated and recorded. Diffracted noise from floating ice and icebergs are examples of source-generated noise that can contaminate the data. Ice contact with the vessels can generate interference noise. Typically,

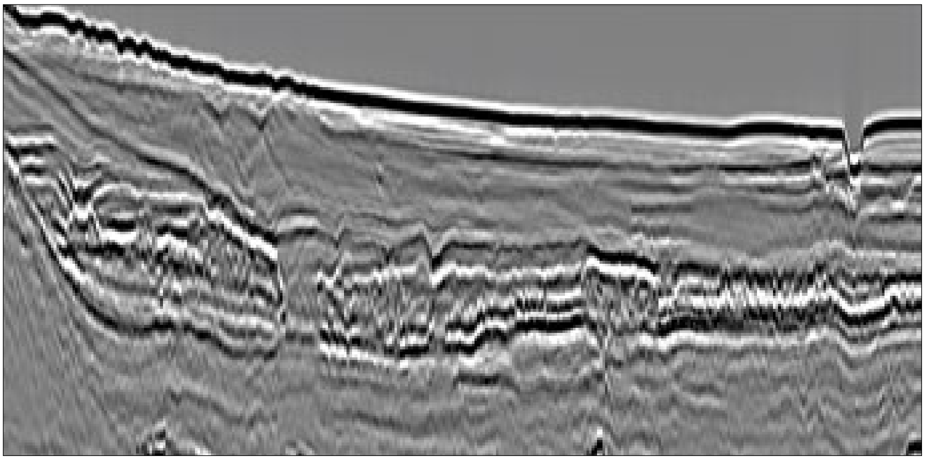

Figure 9. PSTM image of NE GreenlandSPAN data without deghosting. Source is at 18 m depth below sea surface, and streamer is at 20 m depth. A 55 Hz high-cut filtered is applied. Vertical axis is two-way time in seconds. Horizontal axis is distance divided by 6.25 m.

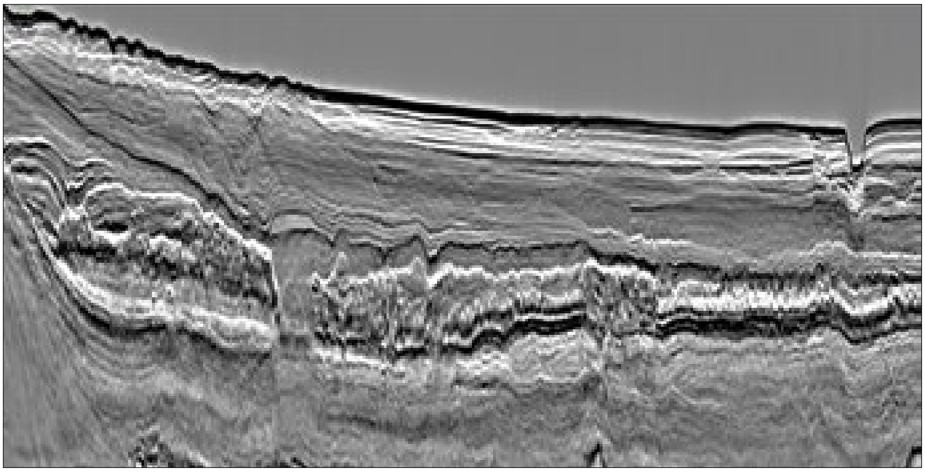

Figure 10. Same data as in Figure 9, imaged after WiBand deghosting. A 160-Hz high-cut filter is applied.

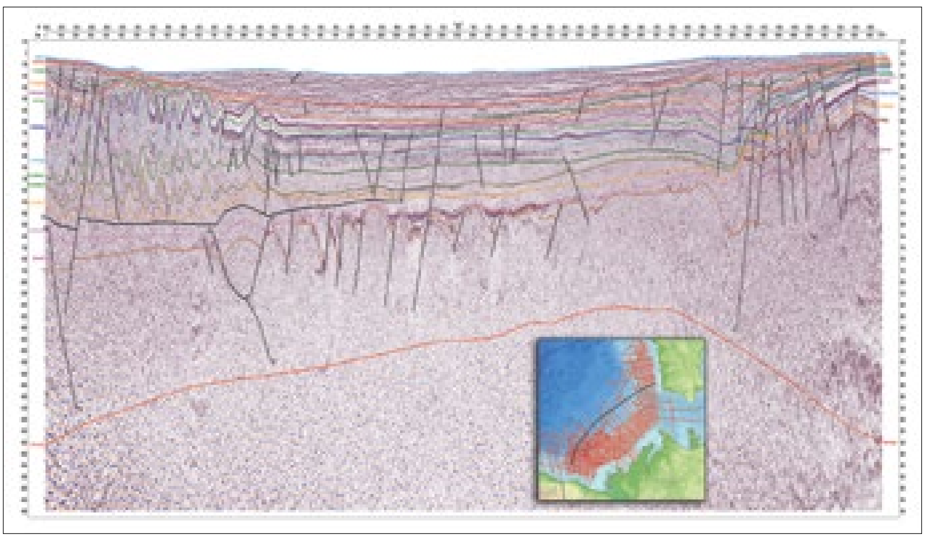

Figure 11. A view of conjugate Arctic margins.

once identified, this noise can be adequately addressed with standard noise-attenuation tools.

In terms of near-surface challenges, imaging issues related to permafrost irregularity are prevalent in land data from the region, but generally pose much less of a problem in marine settings. However, ice and glacier activity can create rugose seabed geometries, which generate multiple reflections that are difficult to remove, particularly from 2D and sparse 3D data. Traditional shallow-water demultiple techniques such as tau-p deconvolution and SRME are effective only when the water bottom is nearly flat, or when the near offset is small enough to capture precritical primary reflections from the sea floor. In recent years, the industry has developed dedicated shallow-water demultiple techniques to address these limitations of traditional methods. ION has also developed apex-shifted multiple attenuation to tackle off-plane multiples that cannot be modeled otherwise from 2D data. In most cases, these methods can adequately attenuate multiples when used together, but improvements are in development to further enhance our ability to image the Arctic subsurface.

As mentioned earlier, seismic data acquisition in ice-infested waters requires towing the streamers and source arrays deep, between 18 and 20 m below the sea surface. Such deep tow can place a severe limit on the resolution of the data, particularly in the shallow sections, if the source and receiver ghosts are not attenuated. In recent years, several new acquisition techniques have been proposed to facilitate deghosting of the recorded data (Posthumus, 1993; Carlson, 2007; Soubaras, 2010). ION developed a processing technique (Zhou, 2012) for deghosting, which addresses both the amplitude attenuation and the phase distortion introduced by ghosts at specific notch frequencies. Usable data, with signal-to-noise ratio above 6 dB at these notch frequencies, are required. The typical result of this process is that, in the first 2 s below the water bottom, data above the ghost notch frequencies can be recovered and imaged instead of being filtered out from the data. Lower frequencies are also enhanced in the same deghosting process. These effects result in much higher resolution in the seismic image (Figures 9 and 10).

Early results

After working through these issues, ION conducted its first formal trial of under-ice acquisition in the summer of 2009 off the northeast coast of Greenland. The objective was to acquire approximately 4000 km of data safely and efficiently, without risk to the crew, environment, or equipment. The trial was considered a success, with just over 5200 km of long-offset, high-quality 2D seismic data acquired without incident to crew or environment, and only 2% technical downtime.

Because the initial deployment offshore Greenland, ION has conducted a number of under-ice Arctic projects in the Beaufort and Chukchi Seas, as well as the high Arctic offshore Russia. Utilizing these unique technologies and methodologies, ION has recorded more than 30,000 km of seismic data under the ice, expending more than one million man hours with a total recordable incident rate (TRIR) of 0.62, well below industry-accepted thresholds. Furthermore, all of these projects have been completed without incident to the environment, a critical factor for E&P activities in the Arctic.

The interpreted seismic section shows a structural and stratigraphic correlation between the Canadian Beaufort areas to Banks Island. Current interpretations allow a better understanding of the present-day petroleum potential in these once conjugate margins. Prior to the advent of under-ice seismic acquisition, this kind of conjugate margin perspective in the Arctic was not possible (Figure 11).

Conclusions

While the technologies discussed in this article provide a means to safely and efficiently acquire data under the ice, the ultimate success of these projects is a result of integrating and operating these technologies with an experienced, multidisciplinary team of experts. ION continues to push the envelope with new tools and techniques to gather modern seismic data in the Arctic. Currently, efforts are underway to further improve the workflow and equipment to acquire 3D marine seismic data in other underexplored, ice-covered environments. TLE

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